Level 2 Model Optimization and New Product Development

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1. Technical Summary

Level 2 System is the primary operation software for production process optimization.

In the current steel industry, it is very common to add microalloys into steels. In deforming the steels with high reduction and lower temperature, the mechanical properties of the steels are greatly increased while the costs are only slightly higher.

In this process, however, it is almost necessary to add metallurgical models into Level 2 System, because the microstructure changes incurred during steel rolling, such as delayed incrystallization during rolling, and metallurgical changes e.g. in the holding of steels in multi-pieces rolling.

Due to changes in chemical compositions, and controlled rolling processes with lower temperature and higher reduction, model factors are changed. So in a rolling mills, up to 100,000 sets of model factors should be redesigned for all the steel grades. This set of models take into account of metallurgical phenomena such as delayed recrystallization and thus induced residual strain due to microalloying elements application. This procedure can also remove learning logics defects existing in almost every Level 2 package in the market.

It can also provide a simple, easy, inexpensive way of Level 2 System upgrade, in which the above-mentioned model factors can be integrated into the Level 2 System. This way of upgrade does not require major modification of the Level 2 source code, but can integrate large number of proven, high-quality models into the current Level 2 System, by using our Guided Two-Parameter Learning.

After the completion of the model upgrading with thus model accuracy increase, further higher-end improvements can be proceeded, such as plate shape improvement and rolled steel property prediction, so a Quality Management System can be developed.

The large number of models have been developed on the basis of the rolling process and product models in the last 30 years during the work in Germany and USA, etc.

2. Microalloys and Necessity for Model Modification

(1) Microalloys and Model Modification
Addition of microalloying elements Nb, V, Ti, Cr, Mo, and Cu, etc., usually increases recrystallization temperature by 50-100°C. This is different from conventional steels which were mainly carbon steels. Moreover, the higher reduction and lower forming temperature incurred in today's rolling practice more likely create residual strain, thus the work-hardening is much higher than conventional rolling, and plate shape may be affected. Softening occurs due to recovery and recrystallization during holding stage in which partial recrystallization temperature range is bypassed. Due to the limited precision and large amount of calculation of metallurgic simulation, it is better to make some off-line design for metallurgic process. Some hard-and-thin grades may enter the two-phase region due to fast temperature drop, resulting in the failure in the conventional Level 2 model.
(2) Machine Learning logic errors
Conventional Level 2 System is a large system, and personnel on material science cannot develop it. It is usually developed by personnel on automation. Therefore, the developers are not familiar with the basic logics of material science, resulting in the logic defects in material properties in Machine Learning. Therefore, we have developed a special machine learning procedure to solve such problems. In fact, Japanese scholars have suggested a unique machine learning method to solve this problem, and claimed that it is very accurate. And we use more than one set, but dozens of thousands of sets, which is far more accurate than that of Japanese counterparts!
(3) Abandoning the Level 2 System after 5-10 years of use
After multiple years of use, the model is no longer suitable for the production line due to the changes of production process, equipment, products and automation modes (unless the factory has a strong person to track the change and make corresponding modification). In a steelplant, Level 2 System is usually the nerve system, while the Level 2 Model is its brain. New Level 2 System package installation accounted for only 0.2% of the equipment investment, and Level 2 System upgrade accounted for only

0.01-0.02% of the equipment investment; it can, however, revolutionize equipment performance. Therefore, many enterprises abandon the Level 2 System and reinstall a new one, usually after the system is used for 5-10 years.

We have developed a set of continuous upgrading scheme, which can avoid the problem of Level 2 System abandonment and reinstallation every 5 to 10 years. This alone can save millions of dollars for enterprises every 5-10 years!

3. A Simple and Efficient Way to Integrate New Models into Level 2

(1) Design of dozens of thousands sets of models

In our Level 2 model upgrade (including new Level 2 System installation), for the extremely complex metallurgical process, offline design was performed according to base models, and then the results were integrated into the online learning of the Level 2 System. In the same time, learning logic defects were fixed, and the solution was put into the large number of data models. Therefore, dozens of thousands sets of models were designed. See the tables below.

Steel grades	Thickness	Product types	Rolling stages	Slab thickness
150	5	4	3	3

In general rolling, one steel mill may have about 100-200 (averagely 150) steel grades based on chemical compositions. For each steel grade, there are 5*4*3*3=180 possible data files (see above table), with each file usually contains over 100 data. A rolling process may be at one of the 150*180=27,000 cases. Every case should have high, medium and low temperature zones, in which each zone has a set of data models (flow stress, etc.). Therefore totally there should be 81,000 data models. Therefore, there are 54000-108000 files for a Level 2 System.

In some situation there may not be all factors. For example, for thin product, the high thickness of the slab may not be used. Therefore, the number of actual factors may be smaller than 54000-108000.

Among the over 100 data in a file, material data for E modulus and specific heat, etc., are strongly temperature dependent; in particular, flow stress coefficients as material factor, temperature factor, etc. , can be determined through offline design.

With difference between microalloyed steels and conventional carbon steels, each data for a microalloyed steel can be totally different from that of the carbon steels. A design for the new data in microalloyed steels is therefore critical for the high accuracy of model prediction.

Due to large number of model calculations, a software package is created. With the software, calculation was made through :

- carbon equivalence formula for hot strength (different from IIW)
- formula for hot strength based on chemical composition
- other procedures and related knowhow

And so on.

(2) A Simple and Efficient Way to Integrate New Models into Level 2

A design for above-mentioned data is critical in the Level 2 System learning. We have developed a simple, easy but Efficient way to integrate large number of new models into Level 2 System, thus to upgrade conventional Level 2 System into the New-Generation one! In this way, only a very few source code modifications is required.

Usually machine learning can be carried out in following ways:

a) . With chemical composition and temperature
b) . a) plus strain
c) . a) plus strain rate
d) . a) plus strain and strain rate

In real operation usually all 4 cases are performed, and the best one was selected. Of those selected, there occurs often the bigger strain factor plus small strain rate factor, or the small strain factor plus bigger strain rate factor. Therefore, both the strain factor and strain rate factor can be any value from large to small. There would be other problems besides this. Those problems reduced the accuracy of the model prediction.

Strain factor and strain rate factor can be determined through machine learning, though their initial values should be determined through design. This learning procedure is called Guided Two-Parameter Learning.
So-called “Guided” is due to the offline design of the material factor and

temperature factor, and "Two-Parameter" is referred to strain factor and strain rate factor, which will be determined through learning with online data. Results from learnt factor, such as strain factor and strain rate factor, is updated in the data file. Only the source code regarding the learning needs modification; others such as use cases/user scenarios, do not need any change. Therefore, source code modification is limited. Major work in this type of projects are in data development. Due to large number of data files, and due to complicated data process, software is developed to do the offline design. In this design software, metallurgic models and manufacturing knowledge is integrated, such as those related to equipment, process, entry material, and automation, etc. This type of software is beyond the reach of pure software engineers. It would also be hard for non-software engineer to integrate such data and learning in the large software such as Level 2 System. The designed data models and the "Guided Two-Parameter Learning" have been successfully applied in Evraz Oregon Steel in USA and NISCO in China for many years. Oregon Steel used to have product defects almost daily in the hard-and-thin (5mm thickness) grades. After installation of new models we created, the defects were totally eliminated. The Level 2 System with metallurgical model, intelligent learning and advanced software engineering, is referred as the New-Generation Level 2 System. Currently, only the author's team possesses this technology.
(3) High prediction accuracy from designed models
With the upgraded model, even rolling in a lower temperature and a larger pass reduction, can still guarantee the good plate/strip shape. Also there is a great room for mechanical properties improvement via thermomechanical processing. In addition, accurate parameter prediction stabilizes the rolled steel properties. With increased and especially stabilized mechanical properties, there is an opportunity to reduce alloy consumption, so the product cost would be greatly reduced and enterprise profit increased. Those effects make it possible for the upgraded Level 2 System to achieve extremely high parameter prediction accuracy, with an error usually only a fraction of that before the upgrade. Level 2 System creates draft schedule based on predicted parameters, which means the quality of the draft schedule is thus greatly improved in this process. Level 2 Model designed and learned in this way is with its name for high

precision, and so the rolling force error is only 1 / 2 to 1 / 3 of that of other advanced Level 2 Systems, that is, in the hard-and-thin products of hot continuous rolling, the error is less than 1%; and in the hard-and-thin products of reversible rolling of medium and heavy plates, it is less than 5%.

4. Advantages of the data, model and software

The advantage of the technology is that it has filled the technology gaps in the world; its advancement exists in that, it has used world's first-class models to upgrade the software that has always been world's first-class!

This technology has been developed in the past 30 years in Germany and USA by combining advantages of several strongest teams in the world, for example, the early model development, the Level 2 creation of Tippins, the Level 2 upgrade in Evraz Oregon Steel, and the further development by adding metallurgical models and intelligent learning, etc., into the system. The successful application in the Oregon Steel and in NISCO has fully demonstrated the advancement of this technology.

(1) Large amount of data collected

I have collected the rolling process parameters from millions of pieces of steel from companies in a large number of projects in the past, and each piece of steel has dozens of data, including plate shape data. I also collected over a million pages of documents from libraries in Germany, USA, Canada and China, etc. For example, in a trip in 2019 with a fortune 500 company to Germany, only from RWTH Aachen library, I have downloaded 200 books in pdf format.

Those data have significance in guiding the production process and optimizing the plate shape. I personally witnessed the strange shape in some companies' hard-and-thin products after water curtain cooling. Combined with all kinds of data, a set of models for optimizing the production process and specifically hard-and-thin product shape were produced. At the same time, it can also be Efficiently optimized through making full use of the roll bending device to reduce center wave or edge wave, and through uniform reduction on the left- and right-hand sides to reduce camber, etc.

Example of field data collection are such as in 1997, Morgan Engineers lived

in Cleveland in a factory for more than three months to collect data of high-speed rolling blocks (speed over 100 m/s). As Senior Engineer of Morgan, I purchased all the microstructure modeling work worldwide using my research funds I myself managed. Field data were also collected during my over 200 consulting projects worldwide. Based on the microstructure model and intelligent learning of the New-Generation Level 2 System, combined with the existing uniform deformation technology and existing data, a complete set of optimization from rolling process stability and property prediction can be achieved. All models are suitable for reversible rolling, hot continuous rolling and other types of flat rolling. Although my business field in intelligent manufacturing has been extended to all new materials and high-end equipment in manufacturing industry. My model development in metal material rolling for more than 30 years is still the core field.
(2) World-class Model
Model development started from a 15-year research project I participated in the Metal Forming Institute in Germany, including over 40 Ph.D. theses. My initial rolling models found applications in German MDS (now SMS) and the Italian Danieli. So I was invited by Danieli to its Italian headquarter for three times. I published my first book in Germany, and my name also stayed on the University’s website for eight years. Before I completed my Ph.D. study in Germany, I was hired by Morgan (now Siemens) in USA as senior engineer in charge of model development. Four years later I created basic model sets and the models were under continued improvements. Later, I worked as a software engineer and software consultant for several steel companies. During the further development of the process models, I also attended computer evening training, and within 8 years I completed 30 computer courses, consisting of classes for B.S., M.S., Ph.D. and Microsoft certification, particularly set up for senior software engineers and software architects. This provided me with sufficient skills to transformed the models into software. This set of models, on the basis of the 15-year of research results in Germany, has been integrated with Morgan’s 5-year rolling mill test data, Morgan’s over 100 years of experience around the world with a large number of first-hand data collected, and my own 200 field projects, and over

1 million pages of data I collected worldwide.

In the latest stages, the model has gradually formed three series of more than 100 sets. The three series are on Metal Flow, Force and Energy Demand, and the Microstructure and Mechanical Property predictions, etc. These models have been continuously improved during on-site projects. Up to later rolling mill field projects, they have been upgraded as New-Generation Level 2 model, including Metallurgical Model, Intelligent Learning and Advanced Software Engineering particularly Uninterrupted Upgraded. Later in NISCO development, I further developed software to design model coefficients, so nearly 100,000 sets of model files can be automatically designed, for over 150 grades for several thousand model grades. See dozens of papers I published in USA and Germany, etc.

(3) World-class Software

So, what was the world-class software before the upgrade with the above-mentioned process models? This was the Level 2 System developed by a team of NASA experts organized by the former US Mill expert TIPPINS, and then further upgraded by Oregon Steel (now EOS) with over 4000 improvements in five years. It also includes a list of Windows features designed for Cascade Steel Level 2 System, etc.

Tippins Level 2 System enjoys high reputation because of its delicate model for learning, parameter calculation, etc., but the Oregon Steel was to make world’s high-end pipeline steels (X80 steels), so vast improvements were made over a period of 5 years, from 1998 to 2003. X80 steels account for almost half of the total output of the Oregon Steel; its X80 steel coils were consumed by a spiral welded pipe factory. The company has a very high requirements for the coil production. Due to the challenge from model prediction errors in hard-and-thin grades, there was products defects almost every day! So from 2005 to 2008, I applied the world's most advanced models to make further upgrade for the Level 2 System. I applied metallurgical models and intelligent learning, etc., and have solved the problems successfully! Six months after the new models were put to use, I went back and was told that it had never had same problem ever since! On the basis, the New-Generation Level 2 System was designed, and a set of technical papers were published from 2009-2012, etc.

This Round of upgrades combined metallurgical model and intelligent learning, with the main purpose to reduce defect rate in rolling of the high grades (such as hard-and-thin products). This technology can also be applied to continuous rolling of hot strips.

5. New-Generation Level 2 for development of new product

In the steel industry the equipment software is mainly reflected in the Level 2 System, in particular Level 2 Model. We have developed a New-Generation Level 2 System and filled technology gaps in the world, because the other suppliers do not contain metallurgical models in Level 2 System, or is very weak in this aspect.

The New-Generation Level 2 System is particularly suitable for developing new steel grades. With optimized properties such as higher strength, and better property stability, reduction of alloy usage is possible. Also, metallurgical Level 2 System, with its function of test production (to run the production with Level 2 simulation only, without equipment movement) , can greatly reduce product defect. In general, new grade development, high-end product manufacture, yield ratio increment, and production stability, etc., can all be achieved by the New-Generation Level 2 System.

Development of new steel grades is not just the chemical composition design, but to design a complete range of controlled rolling and controlled cooling processes as well, in order not only the properties but also the shapes can be achieved. With the metallurgical Level 2 System, microstructure changes of different chemical compositions can be fully calculated and thus, the chemical composition is optimized.

6. Quality Management System for new developments

(1) Quality Management System and modification

At present, various companies mainly use experience to manually design new steel grades and new products. A new software package, Quality Management System, can be developed to completely describe and optimize the design process. Here, designers can be allowed to enter their own correction model to consider the variation from steel grades and production processes. The correction model can also be recommended by the management system with collected research results around the world.

(2) Hot strength (flow stress) and cold strength (rolled steel properties)
In the process of steel forming, the final cold strength (e.g. rolled steel properties) is directly related to the thermal strength (Flow Stress) through chemical composition, phase structure and grain size. Currently, the main problem in rolled steel property prediction is that the accuracy is too low! Through the ingenious combination of the post rolling product property prediction model and the Level 2 Model, the quality of the prediction can be greatly improved through intelligent learning, classification into about 100,000 cases, and continuous optimization of the Level 2 Model. At present, the main reason for the low accuracy of product property prediction is that it is impossible to accurately calculate the grain size after rolling (before the controlled cooling). When the accuracy of the Level 2 Model is sufficient, the rolling force model with high-quality metallurgic model can be used to calculate the grain size and residual stress of each rolling pass. This can be done by economically use of limited resources with machine learning. Since product data has been classified to about 100,000 sets, this alone can greatly improve accuracy in rolled steel property prediction.
(3) Plate shape and other quality parameters
The residual stress is the key parameter in plate shape control. Other models considered for predicting the mechanical properties of steel, are such as phase decomposition model, precipitation model and mechanical property calculation during accelerated cooling. Other quality parameters, such as plate shape, center wave, edge wave, camber, etc., can also be predicted by the quality management system. Due to the limited resources in the rolling process, it is to make Efficient use of resources in machine learning.

7. Summary: Advantage and History

Advantage of the New-Generation Level 2 System
Advantage of the New-Generation Level 2 System exist in that, it can reach extremely high parameter prediction accuracy with its large number of models on product quality and production process, including:

(1) Dozens of thousands of data models for all products

(2) Logics in designing these data model, such as the effects of grain size, chemical composition and process on the strength

(3) Special modeling techniques, which calculates the grain size based on the measured rolling force of each pass, especially of the finishing pass

(4) Residual stress induced by incomplete recrystallization

(5) Prediction models and optimizations for plate profile, center and edge waves, and camber included in its quality prediction section

History Summary of Level 2 System with metallurgical model

(1) Since 1940s: birth of computer and its application in high cost and high-return industries

(2) Since 1980s: full computer and unmanned control in some large industries (though the process may not be optimized); dividing of computer control into Level 1, Level 2 and Level 3 Systems, etc.

(3) Since mid-1990s: gradually using Windows servers (I began to design the Windows-based Level 2 System in 1999, and to run it since 2001; I purchased hardware from Intel and designed software based on Microsoft)

(4) Since 2005, integrating metallurgical models (microstructure models, metallography, etc.) into the Level 2 System (I was the first to integrate those models into Level 2 intelligent system; years later, "the father of microalloying” J. Malcolm Gray, etc., urged the industry to add metallurgical model into Level 2 System)

(5) 2005 and later : I applied metallurgical models, intelligent learning and advanced software engineering (uninterrupted upgrade and engineering recognition of Windows for Level 2 System) worldwide, e.g. in EOS in USA and NISCO in China; the system has been known as the New-Generation Level 2 System